SUSCEPTOR CONNECTION SYSTEM AND ASSOCIATED APPARATUS AND METHOD

BACKGROUND OF THE INVENTION

1) Field of the Invention

The present invention relates to the electrical connection of susceptors and, more particularly, to a system for releasably connecting susceptors and controlling the temperature of the susceptors, such as in an apparatus for heating and processing workpieces.

2) Description of Related Art

Induction heated susceptors are used for heating during various operations, such as in an apparatus for forming, joining, or otherwise processing composite or metallic members. For example, U.S. Patent No. 6,180,932, titled "Brazing Honeycomb Panels with Controlled Net Tooling Pressure," describes a method of induction brazing honeycomb panels in a workcell using susceptor sheets that are heated to a brazing temperature. U.S. Patent No. 5,530,227, titled "Method and Apparatus for Consolidating Organic Matrix Composites Using Induction Heating," and U.S. Patent No. 5,420,400, titled "Combined Inductive Heating Cycle for Sequential Forming the Brazing," describe apparatuses and methods for forming workpieces of organic matrices and metals in which the workpiece is also heated by inducing a current in a susceptor. Generally, an electrical current can be induced in such a susceptor, and the current heats the susceptor until the susceptor reaches a Curie temperature. When a portion of the susceptor reaches the Curie temperature, that portion becomes paramagnetic and the current flows around that portion of the susceptor. Thus, the susceptor can heat the workpiece uniformly to a target temperature as required for forming, bonding, or otherwise processing the workpiece.

The susceptors can be provided as sheets that envelope the workpiece, i.e., first and second susceptor sheets can be disposed on opposite sides of the workpiece. The susceptor sheets are connected at a periphery so that the current induced in the susceptors can flow in a path through both of the susceptors and around the workpiece. For example, the peripheries of the susceptors can be welded together to

achieve a satisfactory electrical contact therebetween. However, welding of the susceptor sheets generally increases the time and cost of the operation. Further, the welding or subsequent destruction of the weld joints (e.g., to remove the workpiece from between the susceptors) can damage the susceptors and prevent their re-use. Alternatively, as described in U.S. Patent No. 6,180,932, the edges of the susceptors can be joined using crimps, gaskets, or a compression edge seal. Such non-weld joints can be formed relatively quickly and can be easily released so that the susceptor can be re-used. However, the contacting portions of the susceptors can oxidize or otherwise degrade during operation of the apparatus, thereby affecting the electrical contact resistance between the susceptors. In some cases, it may be necessary to regularly clean the contacting portions of the susceptors or replace the susceptors to ensure satisfactory electrical contact.

Thus, there exists a need for an improved susceptor connection system and an associated processing apparatus and method. The susceptor connection system should be easily connected and released and should reduce the occurrence of oxidation or other degradation of the contact portions of the susceptors. The connection system should be compatible with susceptors for different processing operations.

BRIEF SUMMARY OF THE INVENTION

The present invention provides a susceptor connection system and an associated apparatus and method. The connection system includes at least one shoe that can be urged against a peripheral edge portion of the susceptors by a compression device. Thus, the shoe places the edge portions of the susceptors in electrical contact. Further, each shoe can define a passage for circulating a coolant to cool the edge portions and thereby reduce the oxidation and contact resistance between the susceptors.

According to one embodiment of the present invention, the system includes first and second susceptors comprised of a conductive material for supporting an induced current flow and thereby heating to a target temperature. Each susceptor can be characterized by a Curie temperature at which the susceptor becomes paramagnetic, and an induction coil can be configured to generate an electromagnetic field and induce a current in the susceptors to heat the susceptors to the target temperature. At least one shoe is adapted to be urged against the peripheral edge portions of the susceptors to place the edge portions of the susceptors in electrical

contact. Each shoe defines a passage for circulating a coolant, such as water, to cool the susceptors. A compression device such as a bladder is positioned adjacent the shoe or the peripheral edge portions of the susceptors. The compression device is configured to urge the shoe against the peripheral edge portions so that the susceptors are placed in electrical contact and the shoe thermally communicates with the peripheral edge portions to cool the peripheral edge portions.

The peripheral edge portion of each susceptor can be plated with a conductive material such as copper, and a central portion of each susceptor inward of the peripheral edge portion can be coated with a material comprising nickel-aluminum. According to one aspect of the invention, the peripheral edge portion of each susceptor defines a plurality of slots extending inward therethrough with tab portions therebetween.

The present invention also provides an apparatus for processing a workpiece at a target temperature. The apparatus includes first and second co-operable dies that are structured to define a die cavity therebetween for at least partially receiving the workpiece, and at least one of the dies defines a contour surface corresponding to a desired configuration of the workpiece. First and second susceptors are disposed in the die cavity. The susceptors are formed of a conductive material capable of supporting an induced current flow and thereby heating the workpiece to a target temperature, e.g., a forming temperature or bonding temperature of the workpiece. An induction coil extends around the susceptors and is configured to generate an electromagnetic field in the susceptors to induce a current in the susceptors and heat the susceptors to a Curie temperature at which the susceptors become paramagnetic. One or more shoes are adapted to be urged against the peripheral edge portions of the susceptors to place the edge portions of the susceptors in electrical contact. A compression device, such as a bladder positioned adjacent the shoe or the peripheral edge portions of the susceptors, is configured to urge the shoe against the peripheral edge portions so that the susceptors are placed in electrical contact and the shoe thermally communicates with the peripheral edge portions to cool the peripheral edge portions. Each shoe defines a passage for circulating a coolant such as water to cool the susceptors.

According to one method of the present invention for releasably connecting susceptors and controlling the temperature in the susceptors, peripheral edge portions of first and second conductive susceptors are urged together with one or more shoes to

place the edge portions in electrical contact. For example, a pressurized fluid can be provided to a bladder to expand the bladder and urge together the shoe and the peripheral edge portions of the susceptors. A current is induced in the susceptors so that the susceptors are heated to a target temperature, e.g., to a Curie temperature of the susceptors at which the susceptors become paramagnetic. Coolant such as water is circulated through a passage defined by the shoe to thereby transfer thermal energy from the peripheral edge portions of the susceptors and control the temperature of the edge portions.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

Figure 1 is a section view in elevation illustrating an apparatus for thermally processing a workpiece, according to one embodiment of the present invention;

Figure 2 is a plan view illustrating the apparatus of Figure 1;

Figure 3 is an enlarged section view illustrating a portion of the apparatus of Figure 1;

Figure 4 is a further enlarged section view illustrating a portion of the connection system of the apparatus of Figure 1;

Figure 5 is a plan view illustrating a portion of the apparatus of Figure 1, including one of the dies with part of the susceptor connection system;

Figure 6 is an enlarged plan view illustrating a portion of Figure 4; and

Figure 7 is an enlarged section view illustrating a portion of a susceptor connection system in an apparatus according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, this invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout.

Referring now to the drawings, and in particular to Figures 1-4, there is illustrated an apparatus **10** for heating a workpiece **12** according to one embodiment of the present invention, e.g., to form, join, or otherwise process the workpiece **12**. The term "workpiece" is not meant to be limiting, and it is understood that the workpiece **12** heated in the apparatus **10** can be simple or complex. The workpiece **12** can be one or more members formed of metallic or composite materials. For example, the workpiece **12** can include one or more flat sheets of material that are superplastically formed or otherwise formed to a desired shape and/or joined by diffusion bonding or other compressive bonding methods. In this regard, the apparatus **10** can include first and second opposed dies **14, 16** that are co-operable and configured to define a die cavity **18** therebetween that is structured to at least partially receive the workpiece **12**. The die cavity **18** can define a contour according to which the workpiece **12** is formed, e.g., corresponding to the dimensions of a panel, spar, beam, or other structural member, which can be used in a variety of applications, for example, as a member of an aircraft wing, aircraft fuselage, other aeronautical vehicle, or the like. The workpiece **12** can also be fabricated for a wide variety of other applications including, without limitation, structural panels or other members for automotive or marine applications or the like.

As shown in Figure 1, the first and second dies **14, 16** are generally mounted to and supported by first and second strongbacks **20, 22**, respectively, which may be secured using a mechanical support structure comprising perpendicular members **26**. A "strongback" is a stiff plate, such as a metal plate, that acts as a mechanical constraint to keep the first and second dies **14, 16** together and to maintain the dimensional accuracy of the dies **14, 16**. As shown in Figure 1, the second die **16** is connected to the second strongback **22**, and the second strongback **22** in turn is connected to a base **24** via multiple actuators **28**, such as hydraulic, pneumatic, or electric rams. The actuators **28** are configured to adjust the second strongback **22** and, hence, the second die **14** toward or away from the base **24**, thereby opening or closing the die cavity **18**. Other methods can also be used for configuring the dies **14, 16**. For example, the first and/or second dies **14, 16** can be slidably adjustable on the perpendicular members **26**, and either or both of the dies **14, 16** can be adjusted on the perpendicular members **26** to open the die cavity **18** using air bladders, hydraulic or pneumatic cylinders, mechanical jacks, levers, and the like. Air bladders or other adjustment devices can also be disposed between the dies **14, 16** and the strongbacks

20, 22. For example, as shown in Figure 1, an intermediate bladder **29** is disposed between the second die **16** and the second strongback **22**. The intermediate bladder **29** defines multiple inflatable portions that can be inflated independently, i.e., a central bladder portion **29a** and a peripheral bladder portion **29b** extending circumferentially around the central portion **29a**. Thus, even if the second strongback **22** flexes slightly, the various portions of the bladder **29a, 29b** can be inflated independently as necessary for maintaining the second die **16** in a planar configuration.

The first and second dies **14, 16** can be formed of a material characterized by a low thermal expansion, high thermal insulation, and a low electromagnetic absorption. For example, the dies **14, 16** can be formed of a material having a thermal expansion of less than about 0.45/(°F x 10^6) throughout a temperature range of between about 0 °F and 1850 °F, a thermal conductivity of about 4 Btu/(hr)(ft)(°F) or less, and substantially no electromagnetic absorption. According to one embodiment of the present invention, the dies **14, 16** are formed of cast ceramic, for example, using a castable fusible silica product such as Castable 120 available from Ceradyne Thermo Materials of Scottdale, Georgia. Castable 120 has a coefficient of thermal expansion less than about 0.45/(°F x 10^6) for low expansion, a thermal conductivity of about 0.47 Btu/(hr)(ft)(°F) to act as a heat insulator, and a low electromagnetic absorption coefficient.

The dies **14, 16** can be at least partially contained within an outer structure such as a box-like structure **30** formed of phenolic material. Further, the dies **14, 16** and phenolic box **30** can be reinforced with fibers and/or fiberglass reinforcing rods **32**. The rods **32** can extend both longitudinally and transversely through the phenolic structure **30** and the first and second dies **14, 16**, as illustrated in Figure 1. To provide a post-stressed compressive state to the first and second dies **14, 16**, the rods **32** can be placed through the phenolic structure **30** and secured within the first and second dies **14, 16** at the time of casting. Thereafter, nuts **34** at the ends of the rods **32** can be tightened to provide the post-stressed compressive state to prevent cracking or other damage to the dies **14, 16**. The first and second dies **14, 16**, the phenolic structure **30**, and the reinforcement rods **32** are described in U.S. Patent No. 5,683,608, entitled "Ceramic Die for Induction Heating Work Cells," which issued on November 4, 1997, and which is assigned to the assignee of the present invention and the entirety of which is incorporated herein by reference.

The first and second dies **14, 16** can define one or more contoured surfaces within the die cavity **18** that correspond to a desired shape of the workpiece **12**. For example, the dies can define a contoured surface **15** with a shape to which the workpiece **12** is to be formed during processing in the apparatus **10**. Alternatively, the contoured surface **15** can correspond to the initial shape of the workpiece **12** so that the dies **14, 16** support the workpiece **12** in its shape during processing. Thus, during processing in the apparatus **10**, the workpiece **12** can be heated, urged against the dies **14, 16**, and cooled in the desired shape. The workpiece **12** can be urged against one or both of the dies **14, 16** by providing a pressurized fluid to the die cavity **18**, e.g., from a source **42** of pressurized fluid that is fluidly connected to the cavity **18** by a pipe **80** (Figure 2). In some embodiments of the present invention, the pressurized fluid can be provided by the source **42** to an inflatable bladder **44** or other structure. For example, an inflatable bladder is described in U.S. Application No. 10/640,188, entitled "Forming Apparatus And Method," filed August 13, 2003, and which is assigned to the assignee of the present invention and is incorporated herein by reference. In other embodiments of the present invention, the workpiece **12** can be heated in the apparatus **10** and processed without forming, e.g., to form bonds in the workpiece **12**, to consolidate the material of the workpiece **12**, to thermally treat the workpiece **12**, and the like.

The workpiece **12** is heated to the target temperature for processing by an induction heater, i.e., an electromagnetic field generator, that induces a current in susceptors **70a, 70b** that thermally communicate with the workpiece **12**. The induction heater can be a plurality of induction coils **50**, such as a solenoid coil as shown in Figures 1 and 2, for inducing an electric current in the susceptors **70a, 70b**. Each induction coil **50** typically includes a plurality of elongate tube sections **52** that are interconnected by curved tube sections **54** to form coils that are positioned proximate to the die cavity **18** and the corresponding susceptors **70a, 70b** in which the current is to be induced. For example, the elongate tube sections **52** can be formed of 1.0 inch diameter copper tubing with a 0.0625 inch wall thickness. The tube sections **52** can alternatively be formed of tubular sections of other sizes and/or with other cross-sectional shapes, for example, square or triangular tubes. The tube sections **52** are generally formed of an electrically conductive material such as copper. Lightly drawn copper tubing can be used so that the tube sections **52** can be adjusted as necessary to correspond to the configuration of the corresponding die **14, 16**. The

tube sections **52** can be positioned relatively close to, such as about 0.75 inches from, the susceptors **70a, 70b**. The curved tube sections **54** are typically disposed outside the dies **14, 16**.

Each curved tube section **54** can be formed of a flexible, non-conductive material such as plastic, and each tube section **52** can be disposed within only one of the two dies **14, 16** so that the tube sections **52, 54** form separate fluid paths in the first and second dies **14, 16**, i.e., the curved tube sections **54** connect the tube sections **52** to other tube sections **52** that are in the same die **14, 16**. The tube sections **52** of the two dies **14, 16** can also be electrically connected by pin and socket connectors **56, 58** as shown in Figure 3, which can be disconnected when the dies **14, 16** are opened to expose the die cavity **18**. The pin and socket connectors **56, 58** are preferably formed of a conductive material such as brass or copper. Thus, the pin and socket connectors **56, 58** maintain electrical conductivity between the tube sections **52** while the generally non-conductive curved sections **54** maintain fluid communication between the tube sections **52**. Further, because the tube sections **52, 54** can form separate fluid paths in the first and second dies **14, 16**, the dies **14, 16** can be opened without disconnecting the tube sections **52, 54**. Therefore, the dies **14, 16** can be separated by disconnecting only the pin and socket connectors **56, 58**, which can be quickly and easily connected and disconnected, thus simplifying the opening and closing of the die cavity **18**.

The induction coil **50** is capable of being energized by one or more power supplies **60**. The power supply **60** provides an alternating current to the induction coil **50**, e.g., between about 3 and 10 kHz. This alternating current through the induction coil **50** induces a secondary current within the susceptors **70a, 70b** that heats the susceptors **70a, 70b** and, thus, the workpiece **12**. The temperature of the susceptors **70a, 70b** and the workpiece **12** can be inferred by monitoring electrical parameters within the one or more power supplies **60**, as described in U.S. Application No. 10/094,494, entitled "Induction Heating Process Control," filed March 8, 2002, and which is assigned to the assignee of the present invention and is incorporated herein by reference. The use of susceptors for brazing, consolidating, and forming operations is also described in U.S. Patent Nos. 6,180,932; 5,530,227; and 5,420,400, each of which is assigned to the assignee of the present invention and is incorporated herein in its entirety by reference.

Due to the low electromagnetic absorption of the dies **14**, **16**, the induction coil **50** induces a current within the susceptors **70a**, **70b** without inducing an appreciable current in the dies **14**, **16**. Therefore, the susceptors **70a**, **70b** can be heated to high temperatures without heating the dies **14**, **16**, thereby saving energy and time during heating and cooling of the workpiece **12**. Further, due to the low thermal expansion of the dies **14**, **16**, the induction coil **50** can be kept relatively cool while the susceptors **70a**, **70b** heat the workpiece **12** without inducing stresses in the dies **14**, **16** sufficient to cause spalling or otherwise degrading the dies **14**, **16**. Additionally, the low thermal conductivity of the ceramic dies **14**, **16** reduces heat loss from the die cavity **18** and, thus, the workpiece **12**.

The induction coil **50** can define a passage **62** for circulating a cooling fluid, such as water, from a fluid source **64**, as shown in Figure 1. A pump circulates the cooling fluid from the fluid source **64** through the passage **62**. The cooling fluid cools the induction coil **50** to maintain low electrical resistivity in the coil **50**. In addition, by positioning the induction coil **50** uniformly relative to the susceptors **70a**, **70b**, the induction coil **50** can be used to heat the susceptors **70a**, **70b** uniformly, and the cooling fluid can be used to transfer thermal energy from the susceptors **70a**, **70b** to cool the susceptors **70a**, **70b**. Thus, the cooling fluid can be used to cool the workpiece **12** after the workpiece **12** has been thermally processed.

The susceptors **70a**, **70b** are formed of a material that is characterized by a Curie temperature at which the susceptors **70a**, **70b** become paramagnetic, for example, a ferromagnetic alloy such as an alloy comprising iron and nickel. Susceptors having Curie temperatures at which each susceptor becomes non-magnetic, or paramagnetic, are described in U.S. Patent No. 5,728,309, entitled "Method for Achieving Thermal Uniformity in Induction Processing of Organic Matrix Composites or Metals," which issued on March 17, 1998; U.S. Patent No. 5,645,744, entitled "Retort for Achieving Thermal Uniformity in Induction Processing of Organic Matrix Composites or Metals," which issued on July 8, 1997; and U.S. Patent No. 5,808,281, entitled "Multilayer Susceptors for Achieving Thermal Uniformity in Induction Processing of Organic Matrix Composites or Metals," which issued on September 15, 1998, each of which is assigned to the assignee of the present invention and is incorporated herein by reference.

The susceptors **70a**, **70b** can be provided as separate first and second portions **70a**, **70b** on the first and second dies **14**, **16** so that when the dies **14**, **16** are opened

the susceptors **70a**, **70b** are also opened and the workpiece **12** and/or bladder **44** can be inserted or removed from the die cavity **18**. For example, the susceptors **70a**, **70b** can be cast within either or both of the first and second dies **14**, **16** or otherwise disposed thereon. Alternatively, the individual susceptors **70a**, **70b** can be connected to the respective dies **14**, **16** by studs, rivets, or other connectors such as screws, bolts, clips, weld joints, and the like. In any case, the susceptors **70a**, **70b** can be configured on the dies **14**, **16** such that peripheral edge portions **72a**, **72b** of the susceptors **70a**, **70b** make electrical contact when the dies **14**, **16** are closed. Further, the apparatus **10** can include one or more shoes **90** for urging the longitudinally opposite edge portions **72a**, **72b** of the susceptors **70a**, **70b** together. Each shoe **90** can be formed of one or more elongate members, each of which defines a passage **92** through which a coolant can be circulated during operation of the apparatus **10**. For example, as illustrated in Figures 4-6, each shoe **90** can be formed of two parallel copper tubes that are rectangular in cross-section and relatively thick-walled. The passages **92** extending through each of the tubes are connected to a coolant source **94**. In particular, the passages **92** are connected in a series configuration by connection tubes **96** to the coolant source **94** in Figure 4, though various other configurations can also be used, including a configuration in which each of the passages **92** of the shoes **90** is connected in parallel to the source **94**.

A compression device can also be positioned adjacent to each shoe **90** and configured to urge the respective shoe **90** against the peripheral edge portions **72a**, **72b** of the susceptors **70a**, **70b** to electrically engage the edge portions **72a**, **72b**. For example, the compression device can be an inflatable bladder **100** that is fluidly connected to a source **102** (Figure 5) of pressurized fluid so that the bladder **100** can be inflated by the source **102** to compress the edge portions **72a**, **72b** between the shoe **90** and one of the dies **14**, **16**. The inflatable bladders **100** can be formed of metal such as 300 series austenitic stainless steel, and the source **102** can be a compressor or pressure vessel that is configured to provide compressed air or other gas to the bladders **100**. Thus, when the dies **14**, **16** are closed, the bladder **100** at the left side of the apparatus **10** (as shown in Figures 3 and 5) is disposed between the shoe **90** and the second die **16**, and the bladder **100** at the right side of the apparatus **10** is disposed between the shoe **90** and the second die **16**. As the bladders **100** are inflated, the shoes **90** urge the peripheral portions **72a**, **72b** of the susceptors **70a**, **70b**

against the first die **14** and compress the portions **72a, 72b** together to achieve a satisfactory electrical connection therebetween.

The susceptors **70a, 70b** are heated through eddy current heating to the Curie temperature of the susceptors **70a, 70b,** whereupon the susceptors **70a, 70b** become paramagnetic and do not rise appreciably further in temperature. Eddy current heating of the susceptors **70a, 70b** results from eddy currents that are induced in the susceptors **70a, 70b** by the electromagnetic field generated by the induction coil **50**. The flow of the eddy currents through the susceptors **70a, 70b** results in resistive heating of the susceptors **70a, 70b**. If some portions of the susceptors **70a, 70b** are heated more quickly than other portions, the hotter portions will reach the Curie temperature and become paramagnetic before the other, cooler portions of the susceptors **70a, 70b**. The magnetic flux lines will then flow through the cooler magnetic portions, i.e., around the hotter, paramagnetic portions of the susceptors **70a, 70b**. The current in the susceptors **70a, 70b,** which flows substantially perpendicular to the magnetic flux but is proportional to the magnetic flux density, causes the cooler portions to also become heated to the Curie temperature. Therefore, even if some portions of the susceptors **70a, 70b** heat at different rates, the entire susceptors **70a, 70b** are heated to a uniform Curie temperature. Further, the susceptors **70a, 70b** can act as a magnetic shield that prevents the induction coil **50** from inducing a current in the workpiece **12**. As such, the induction coil **50** does not heat the structural workpiece **12** directly, but rather heats the susceptors **70a, 70b,** which, in turn, act as a heat source in thermal communication with the workpiece **12**.

The Curie temperature of the susceptors **70a, 70b** can correspond to the target temperature of the workpiece **12,** e.g., a forming temperature at which the workpiece **12** can be formed and/or a bonding temperature at which the workpiece **12** can be bonded. For example, the Curie temperature of the susceptors **70a, 70b** can be equal to or slightly greater than the target temperature of the workpiece **12** so that the workpiece **12** is heated to the target temperature when the susceptors **70a, 70b** are heated to the Curie temperature. Thus, the susceptors **70a, 70b** can be used to heat the workpiece **12** uniformly to the target temperature so that the workpiece **12** can be formed, bonded, or otherwise processed.

The susceptors **70a, 70b** can be formed of a variety of materials including iron, nickel, cobalt, and alloys thereof, and the composition of the susceptors **70a, 70b** can be designed to have a Curie temperature for achieving a desired target

temperature that is appropriate for a particular type of processing of a workpiece formed of a particular type of material. For example, susceptors **70a, 70b** with a Curie temperature of about 750° F can be used for forming a composite workpiece of Ultem® resin. In one embodiment, the susceptors **70a, 70b** are formed of an alloy that typically includes approximately 53% iron, 29% nickel, 17% cobalt, and 0.2% chromium, generally referred to as Kovar®, a registered trademark of CRS Holdings, Inc. This alloy has a Curie temperature of about 750° F. In any case, the susceptors **70a, 70b** can be removable from the dies **14, 16** and can be replaced if they become worn or if it is desired to install susceptors **70a, 70b** with a different Curie temperature. Thus, the apparatus **10** can be used for processing workpieces **12** formed of a variety of materials or in a variety of processing operations.

Due to the electrical contact between the susceptors **70a, 70b**, eddy currents induced in the susceptors **70a, 70b** by the induction coils **50** can flow throughout the susceptors **70a, 70b**, and, in particular, between the susceptors **70a, 70b** through the peripheral portions **72a, 72b** in contact by virtue of the shoes **90** and the compression devices **100**. Each shoe **90** thermally communicates with the peripheral edge portions **72a, 72b** to cool the peripheral edge portions **72a, 72b**. In this regard, the shoes **90** transfer thermal energy from the peripheral edge portions **72a, 72b** of the susceptors **70a, 70b** to the coolant circulated through the shoes **90**, thereby cooling the edge portions **72a, 72b**. The temperature of the edge portions **72a, 72b** of the susceptors **70a, 70b** can be controlled by adjusting the temperature and flow rate of the coolant. For example, the coolant can be water that is circulated to the shoes **90** at room temperature, and the coolant can be circulated at a sufficient rate to cool the edge portions **72a, 72b** of the susceptors **70a, 70b** to a temperature of about 100 °F or less. Thus, the peripheral edge portions **72a, 72b** of the susceptors **70a, 70b** can be maintained at a relatively low temperature, even while a central portion **74a, 74b** of each susceptor **70a, 70b** inward of the peripheral edge portions **72a, 72b** is heated by the induced current to the target processing temperature.

Each of the susceptors **70a, 70b** can also define slots **76** extending inward through the peripheral edge portions **72a, 72b** and tab portions **78** of the susceptors **70a, 70b** between the slots **76**. The slots **76** can reduce the stress in the susceptors **70a, 70b** that might otherwise result due to the thermal gradients existing between the heated inward central portion **74a, 74b** of the susceptors **70a, 70b** and the cooled peripheral portions **72a, 72b**. At least part of the tabs **78** can be plated with a

conductive material such as copper to facilitate the electrical connection between the susceptor sheets **70a, 70b**. For example, the opposed surfaces **79** of the tabs **78** can be plated with copper as shown in Figures 4-6. The remainder of the susceptor sheets **70a, 70b**, including the central portion **74a, 74b** of each susceptor **70a, 70b**, can have an oxidation resistant coating, such as a nickel aluminide coating that is flame-sprayed or otherwise disposed on the surface of the susceptors **70a, 70b**. A description of a susceptor with a nickel aluminide coating is provided in U.S. Application No. 10/032,625, entitled "Smart Susceptors with Oxidation Control," filed October 24, 2001, and which is assigned to the assignee of the present invention and is incorporated herein by reference.

As shown in Figures 4 and 5, the apparatus **10** can also include a cavity seal **82** that is disposed between the dies **14, 16**, for example, between the susceptors **70a, 70b** at a location between the die cavity **18** and the peripheral edge portions **72a, 72b**. The cavity seal **82** can be a ridge-like structure that extends continuously around the die cavity **18** and hermetically seals the die cavity **18** during operation to prevent pressurized gas in the cavity **18** from leaking. The cavity seal **82** can also be formed of a nonconductive material so that the induced current flowing between the two susceptors **70a, 70b** flows through the peripheral edge portions **72a, 72b** rather than through the cavity seal **82**. For example, for applications in which the target temperature of the apparatus **10** is below 550 °F, the cavity seal **82** can be formed of silicon based elastomeric materials. For applications in which the target temperature is above 550 °F, the seal **82** can be formed of a composite material such as Al_2O_3 fibers disposed in a matrix of Al_2O_3, SiC fibers disposed in a matrix of SiC, or other dielectric materials. In addition, a liner **84** or other barrier material can be provided between each die **14, 16** and the adjacent susceptor **70a, 70b**. The liner **84** can be formed of dielectric and/or composite materials similar to those used for the seal **82**. Die liners are further discussed in U.S. Patent Application Publication No. 2003/0106890, titled "Induction Processable Ceramic Die with Durable Die Liner," which was published June 12, 2003 and is assigned to the assignee of the present invention, and the entirety of which is incorporated herein by reference.

One or more pipes **80**, tubes, or other fluid communication devices can extend through the cavity seal **82**, through one of the susceptors **70a, 70b**, or between the cavity seal **82** and one of the susceptors **70a, 70b** as shown in Figure 2. For example, the pipe **80** fluidly connects the die cavity **18** with the pressurized fluid source **42**, so

that the fluid source **42** can supply fluid to the die cavity **18** while the cavity **18** is sealed by the cavity seal **82** during processing. Additional pipes can also be provided for evacuating the cavity **18**.

During operation according to one embodiment of the present invention, the workpiece **12** is a blank, which can be cut to a predetermined shape that corresponds to the desired dimensions of a structural member to be formed. The workpiece **12** is disposed in the die cavity **18**, and one or both of the dies **14, 16** are adjusted to close the die cavity **18**. The die cavity **18** is hermetically sealed by the cavity seal **82**. The pin and socket connectors **56, 58** can be configured to engage as the die cavity **18** is closed so that the induction coil **50** forms a circuit extending around the workpiece **12**. The susceptors **70a, 70b** are also electrically engaged, by urging the dies **14, 16** together and inflating the bladders **100** to urge the shoes **90** against the susceptors **70a, 70b**, thereby compressing the longitudinally opposite peripheral portions **72a, 72b** of the two susceptors **70a, 70b** between the shoes **90** and the first die **14**. It is appreciated that the compression devices **100** and the shoes **90** can be configured to urge the susceptors **70a, 70b** against either of the dies **14, 16**, or each compression device **10** can be disposed opposite the susceptors **70a, 70b** from the respective shoe **90** so that the susceptors **70a, 70b** are compressed between each compression device **100** and the respective shoe **90**. In any case, the peripheral edge portions **72a, 72b** of the susceptors **70a, 70b** are urged together to thereby electrically engage the susceptors **70a, 70b** and so that the shoes **90** can thermally communicate with the susceptors **70a, 70b** to control the temperature of the peripheral portions **72a, 72b**.

The workpiece **12** is then heated, for example, by energizing the power supply **60** so that the induction coil **50** provides an electromagnetic field that induces a current in the susceptors **70a, 70b**. The susceptors **70a, 70b** can be heated to a Curie temperature that corresponds to the forming temperature of the workpiece **12**, for example, about 750° F, within about 15 to 30 seconds, though shorter and longer heating cycles are possible. Before, during, or after the heating of the workpiece **12**, the pressurized fluid can be provided to the die cavity **18** from the pressurized fluid source **42**, e.g., to form the workpiece **12** against the contoured surface **15** or to form bonds in the workpiece **12**. While the central portions **74a, 74b** of the susceptors **70a, 70b** are heated to the target temperature, the temperature of the peripheral edge portions **72a, 72b** is controlled by circulating the coolant through the shoes **90**. For example, water can be circulated from the coolant source **94**, through the shoes **90**,

and discharged from the shoes **90**. The water can be cooled and recirculated or discarded after use. In any case, the temperature of the peripheral edge portions **72a, 72b** can be maintained below a maximum temperature, e.g., of about 100 °F. By reducing the operating temperature of the contacting peripheral edge portions **72a, 72b** of the susceptors **70a, 70b**, oxidation of the susceptors **70a, 70b** and contact resistance between the contacting opposed portions **79** of the two susceptors **70a, 70b** can be minimized.

After the workpiece **12** is formed against the contoured surface **15**, the pressure in the bladder **44** can be maintained while the workpiece **12** cools. For example, the workpiece **12** can be cooled in the apparatus **10** to below a plasticizing temperature so that the workpiece **12** can be removed from the die cavity **18** without substantially plastically deforming the workpiece **12** from its shape. A coolant fluid such as the pressurized fluid from the source **42** can be circulated through the die cavity **18** while the cavity is pressurized to cool the workpiece **12**.

In addition, heat treatments can be performed on the workpiece **12** while the workpiece **12** is in the die cavity **18**. For example, the workpiece **12** can be heated and cooled according to a predetermined schedule. Such heat treatment are discussed in U.S. Application No. 10/431,295, entitled "Method and Apparatus for Induction Heat Treatment of Structural Members," filed May 7, 2003, and which is assigned to the assignee of the present invention and is incorporated herein by reference.

Figure 7 illustrates another embodiment of the present invention that includes a clamping device **110** disposed between the dies **14, 16**. Generally, the clamping device **110** can be used in conjunction with the shoes **90** and the bladder **100** to electrically engage the susceptors **70a, 70b** while allowing the peripheral edge portions **72a, 72b** of the susceptors **70a, 70b** to adjust as the susceptors change size as a result of changes in temperature. In this regard, stresses in the susceptors **70a, 70b** can be reduced during processing. In particular, the clamping device **110** is received in a space **112** between the dies **14, 16** at one of the longitudinal ends of the susceptors **70a, 70b**. It is appreciated that another clamping device can also be provided at the longitudinally opposite ends of the susceptors **70a, 70b**. As illustrated, the clamping device **110** is c-shaped with first and second arm members **114, 116**. The arm members **114, 116** are releasably attached by a pin **118** or other releasable connection device. With the pin **118** released, the arms **114, 116** can be separated, e.g., so that the first and second arms **114, 116** can remain in contact with

the respective dies **14, 16** as the dies **14, 16** are opened. With the pin **118** engaged, the arms **114, 116** are secured together so that the peripheral edge portions **72a, 72b** of the susceptors **70a, 70b**, the shoe **90**, and the bladder **100** are constrained therebetween. In fact, as the bladder **100** is inflated, the clamping device **110** resists the expanding action of the bladder **100** so that the susceptors **70a, 70b** are squeezed between the shoe **90** and the first arm member **114**. The clamping device **110** can be smaller than the space **112** between the dies **14, 16** and each arm **114, 116** can be adjustable relative to the dies **14, 16** so that the peripheral edge portions **72a, 72b** of the susceptors **70a, 70b** and the clamping device **110** can move as the susceptors **70a, 70b** expand or contract during thermal processing.

Each of the arm members **114, 116** of the clamping device **110** can be formed of a heat resistant material such as 300 series stainless steel. Further, the arms **114, 116** can define passages **120** through which a coolant fluid can be received. For example, the passages **120** can be configured to receive a flow of the coolant from the coolant source **94**. Thus, the clamping device **110** can be configured to remove thermal energy from the peripheral edge portions **72a, 72b** of the susceptors **70a, 70b**, thereby controlling the temperature of the susceptors **70a, 70b** in conjunction with the shoes **90**.

During one typical operation of the embodiment of Figure 7, the workpiece **12** and susceptors **70a, 70b** are disposed in the die cavity **18**, with the peripheral edge portions **72a, 72b** of the susceptors **70a, 70b** between the arms **114, 116** of the clamping device **110**, which can be separated with the dies **14, 16**. The arms **114, 116** of the clamping device **110** are aligned, e.g., automatically with springs or actuators, so that the pin **118**, which can be disposed in one of the arm members **114, 116**, is aligned with a hole or device in the opposite arm member **114, 116** for engaging the pin **118**. The dies **14, 16** are then closed, and the pin **118** engages the arms **114, 116** so that the arms **114, 116** are secured together with the susceptors **70a, 70b** therebetween as shown in Figure 7. In some cases, the engagement of the pin **118** can be triggered automatically, e.g., by an expanding force on the arms **114, 116** provided by a partial inflation of the bladder **110**. In any case, with the clamping device **110** clamping the peripheral edge portions **70a, 70b** together and the bladder **110** inflated, the susceptor sheets **70a, 70b** are squeezed between the shoe **90** and the first arm **114**. The dies **14, 16** can then be opened slightly, and the susceptors **70a, 70b** at least partially heated so that the susceptors **70a, 70b** thermally expand, with the peripheral

edge portions **72a**, **72b** and, hence, the clamping device **110**, moving outward from the die cavity **118** accordingly. Once the susceptors **70a, 70b** have reached an expanded configuration, the die cavity **18** can be closed again, and the thermal processing operation can be performed.

Many modifications and other embodiments of the invention set forth herein will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.